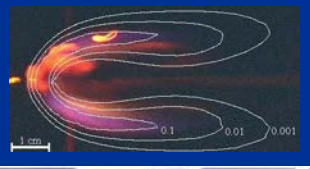
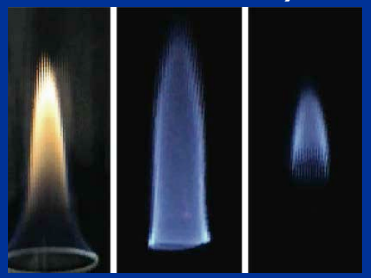
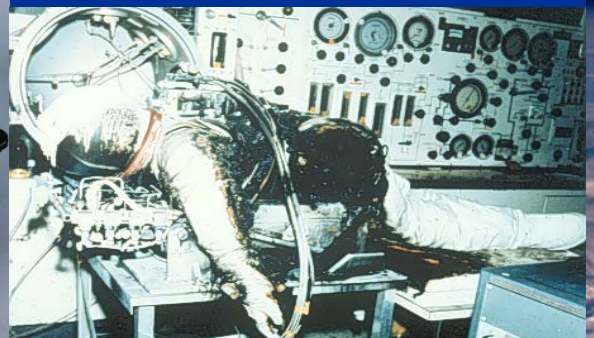
NASA Microgravity Combustion Program



October 20, 2015



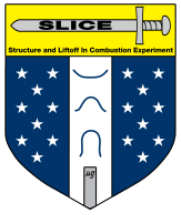


David L. Urban
NASA GRC
Cleveland OH

NASA Microgravity Combustion Program

Combustion Science

- Spacecraft fire safety
- Droplets
- Gaseous – Premixed and Non-Premixed
- Solid Fuels
- Supercritical reacting fluids



Outline

- Historic Program
- Current Status
- Completed Content
- Current & Proposed Content
- Current Schedule
- Cool Flames
- Future Investigations
- Proposed Investigations: Supercritical Reactions
- Drop Tower Modification Proposal
- Saffire
- Open Science
- Opportunities

Historic Program

- 1989-2006: Large ground-based program and robust set of flight experiments building upon shuttle based payloads toward ISS experiments
- 2006-present: change in focus toward “exploration” i.e. research directed to support manned exploration of space. In the case of combustion research, this focused on Spacecraft Fire Safety and In Situ Research Utilization (ISRU).
- Owing to pressure from Congress, a balance was developed that included a substantial fraction of fundamental research in addition to exploration research.
- This has transitioned to include use of the ISS by the Center for Advancement of Science in Space (CASIS).

Current Status

- Ongoing Space Life and Physical Sciences (SLPS) program now constrained by on-orbit resources (became a serious problem for combustion in 2014).
- Management of 50% of the ISS resources has been allocated to CASIS (Center for the Advancement of Science in Space) as manager of the International Space Station U.S. National Laboratory.
- Commercial entities and other government agencies can approach CASIS for access to the ISS.
- Mutually beneficial collaboration between CASIS and SLPS experiments is encouraged.
- Similar benefits can be achieved through Russian collaboration.

Combustion Science completed content

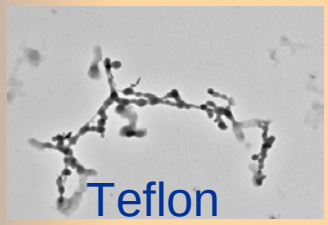
Conducted in the Microgravity Science Glovebox

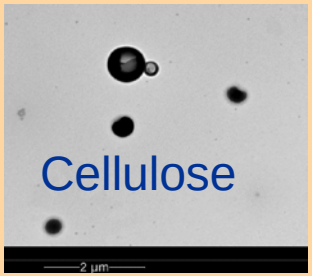
Fire Detection:

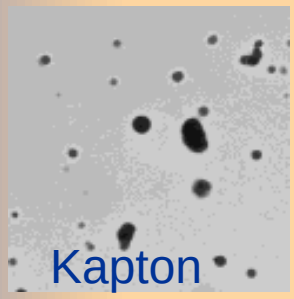
- Smoke Aerosol Measurement Experiment (SAME) (Urban, Mulholland, Cleary, Yang)

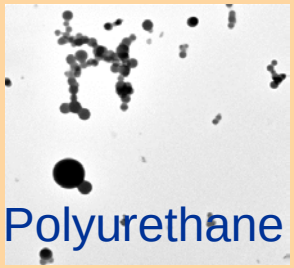
Solid Fuel Flammability

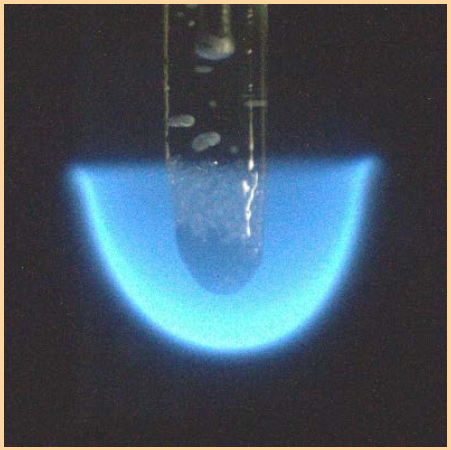
- Burning And Spread over Solids (BASS) (Bhattacharjee, Miller, Olson, T'ien, Pello)











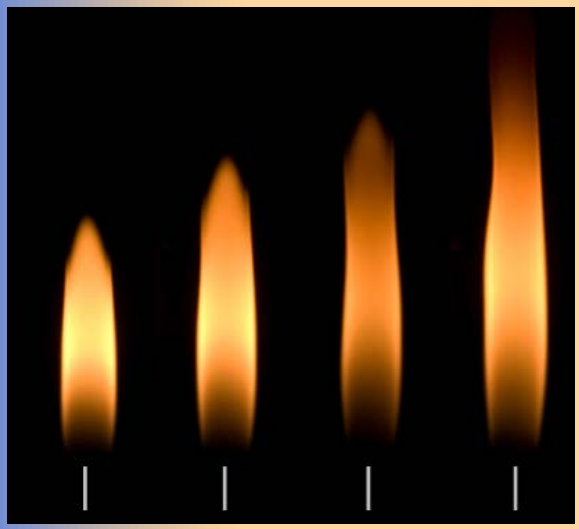
PMMA rod in stagnation flow

Combustion Science completed content

Conducted in the Microgravity Science Glovebox

Non-premixed Gaseous Flames

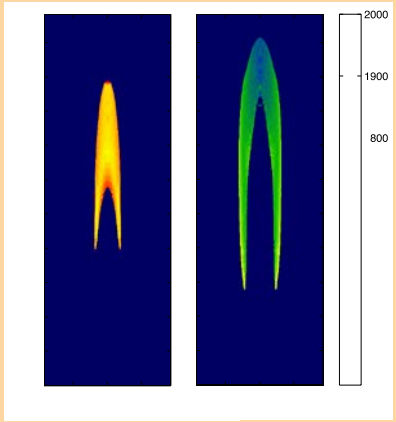
- Smoke Point in Co-Flow Experiment (SPICE) (Urban-Sunderland)
- Structure & Liftoff In Combustion Experiment (SLICE) (Smooke-Long)



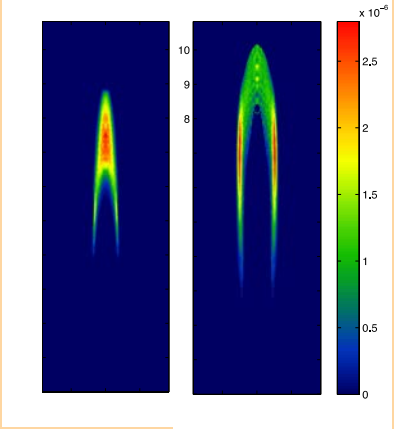
Diluted Propylene
Smoke Points

1g µg

Photo



Soot temperature



Soot volume fraction

Methane Results

Combustion Science current content

Droplet Combustion (Williams, Dryer, Farouk, Nayagam, Shaw, Avedesian, Dietrich, Choi)

- MDCA – FLEX, FLEX-I (completed)
- MDCA – FLEX-2, FLEX-J (Chemical kinetics and transport)
- MDCA - Cool Flames

Non-premixed Gaseous Flames

- ACME – BRE (Burning Rate Emulator) (Quintiere-Sunderland)
- ACME – CLD Flame (Coflow Laminar Diffusion Flame) (Smooke-Long)
- ACME – E-FIELD Flames (Electric-Field Effects) (Dunn Rankin)
- ACME – Flame Design (*soot inception and transport*) (Axelbaum, Sunderland, Chao)
- ACME – s-Flame (Structure and Response of Spherical Diffusion Flames) (Law and Tse)

Combustion Science current content

Solid Fuel / Flammability

- SoFIE - Residence Time Driven Flame Spread (Bhattacharjee)
- SoFIE - Narrow Channel Validation (Miller, Wichman)
- SoFIE - Spacecraft Materials Microgravity Research on Flammability (Olson)
- SoFIE - Growth and Extinction Limit (T'ien)
- SoFIE - Material Ignition and Suppression Test (Pello)
- FLARE – Flammability Limits At Reduced-g Experiment (JAXA-Fujita)

Super Critical Water Mixture

- SCWM – Supercritical Water Mixture Experiment (Hicks)

Combustion Science proposed content

"CombustionLab" Workshop

Held last year at American Society for Space and Gravitational Research Conference. Considered opportunities in 6 areas:

- Spacecraft Fire Safety
- Droplets, Sprays and Aerosols
- Premixed Flames
- Non-premixed Flames
- Heterogeneous Reaction Processes
- High Pressure and Supercritical Reacting Systems

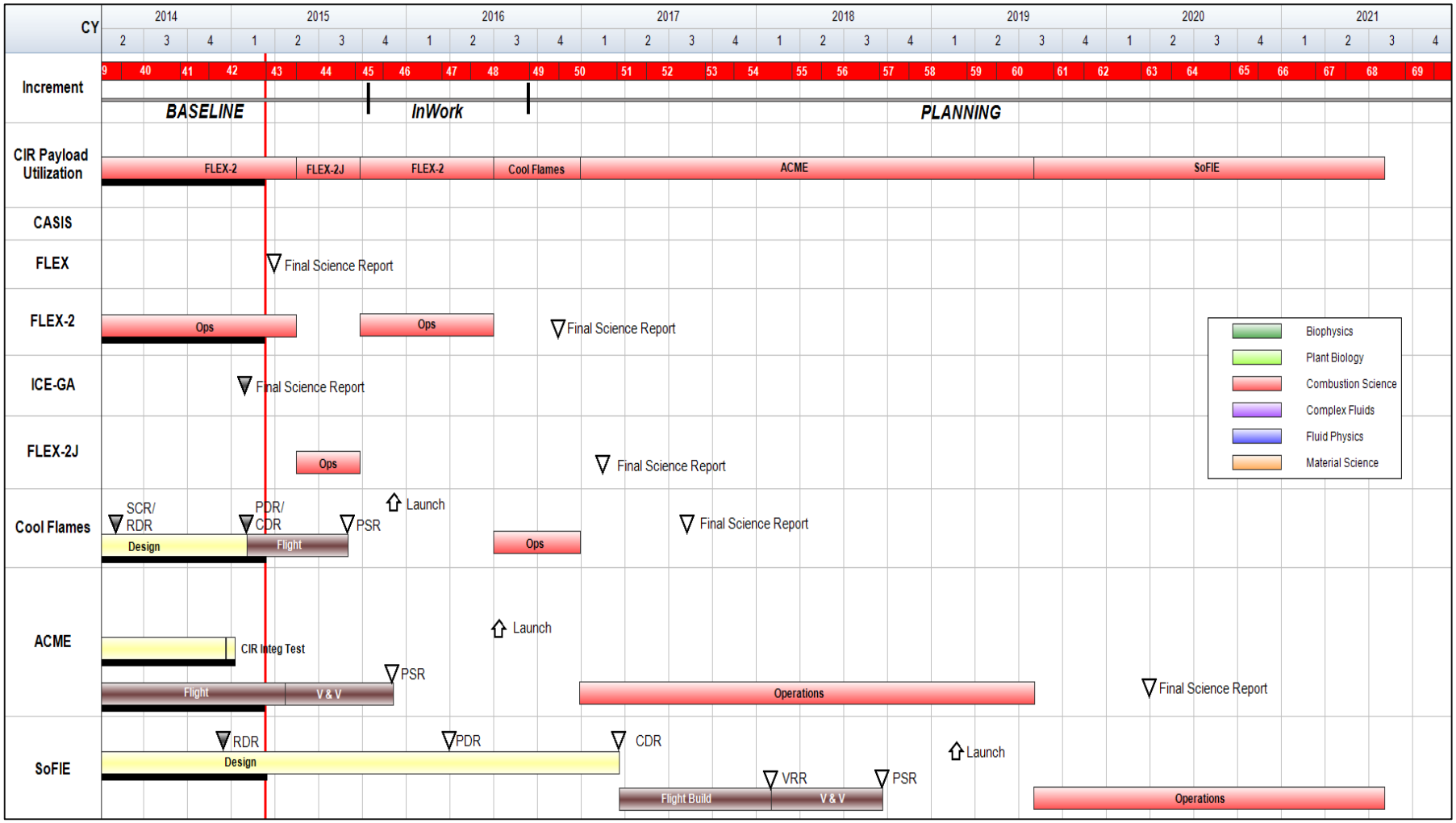
Selected from the highest rated concepts from CombustionLab for the next investigation:

High-Pressure / Super Critical Water Oxidation

- High Pressure Droplets and Sprays - Transport and Combustion Processes
- SCWO – Supercritical Water Oxidation Experiment

Combustion Integrated Rack (CIR) Payload Utilization Schedule

03/12/2015

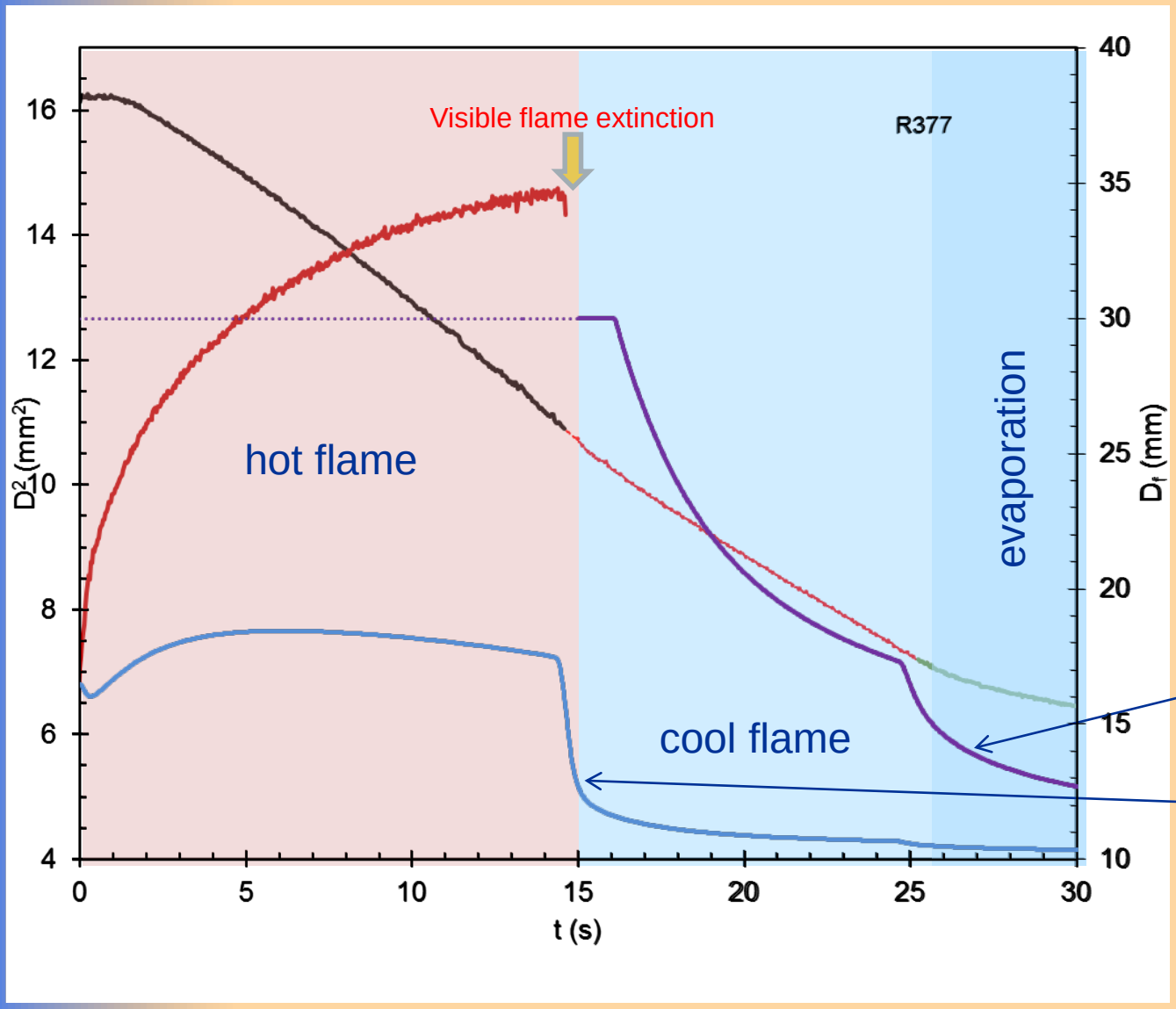


Cool Flame - Droplet Combustion

- FLEX tests examined methanol and heptane droplet combustion in quiescent microgravity ambient environments
- Early tests showed unusual behavior of heptane droplets after radiative extinction of the (visible) hot flame
  - The droplet continued to vaporize at a rate nearly equal to that it did during the hot flame
  - This linear vaporization ended with an abrupt plateau at a finite droplet size
  - The plateau coincided with the formation of a large ‘cloud’ or ‘fog’ surrounding the droplet
- Initial cool flame burning ideas rejected because that was unlikely or ‘impossible’
- Sustained cool flame burning confirmed by theoretical and numerical models with detailed and reduced chemistry

Cool Flame Burning

FLEX Cool Flame – N-Decane in O2/N2 environment



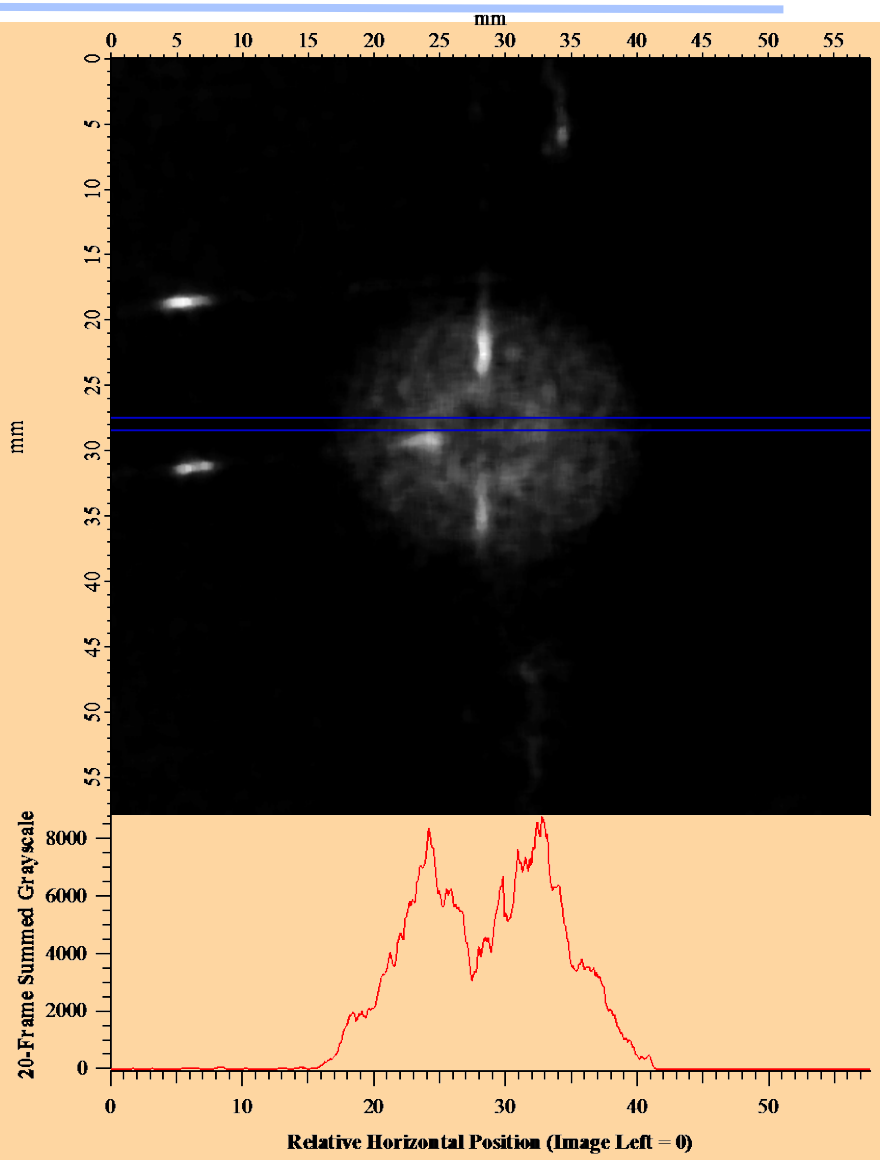
D0 = 4.05 mm
Fuel – n-decane
Oxygen – 25%
Nitrogen – 75%
Pressure – 0.5 atm

narrow-band radiation

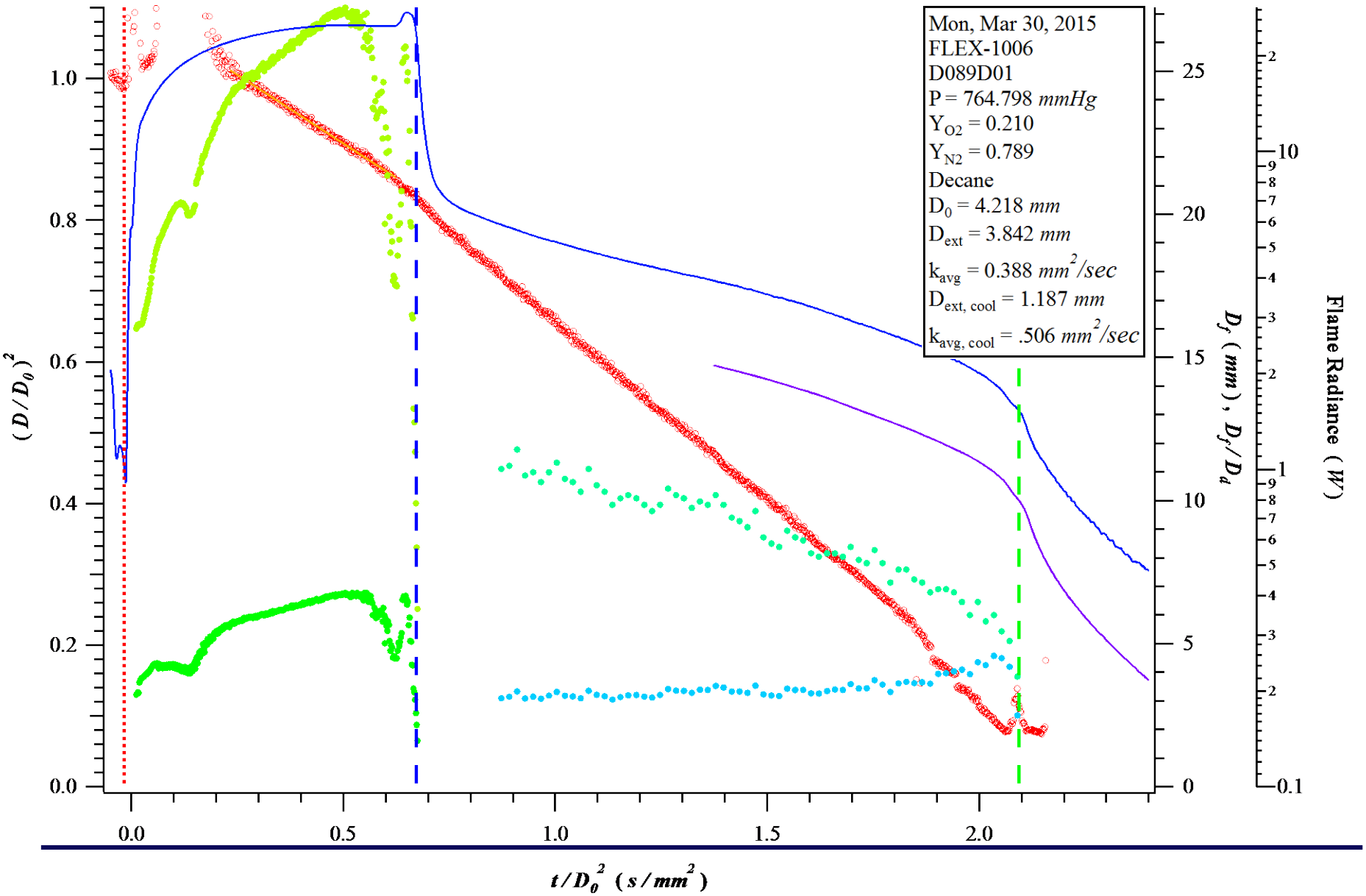
wide-band radiation

Cool Flame Visualization

- Cool flames are invisible to the CIR and MDCA cameras as configured for FLEX
- Reconfigured *OH** camera (intensified) to visualize cool flame
  - Removed 310 *nm OH** filter (broadband flame emission)
  - Maximized gain during cool flame
  - Turn off gain during hot flame
  - Use radiometer output to determine presence of cool flame
- Flame still not discernible in a single image
- Frame average over 0.5 to 1.5 *s*
- Able to ‘see’ cool flame
- Resulting size and standoff ratio in good agreement with theory and models of cool flame burning

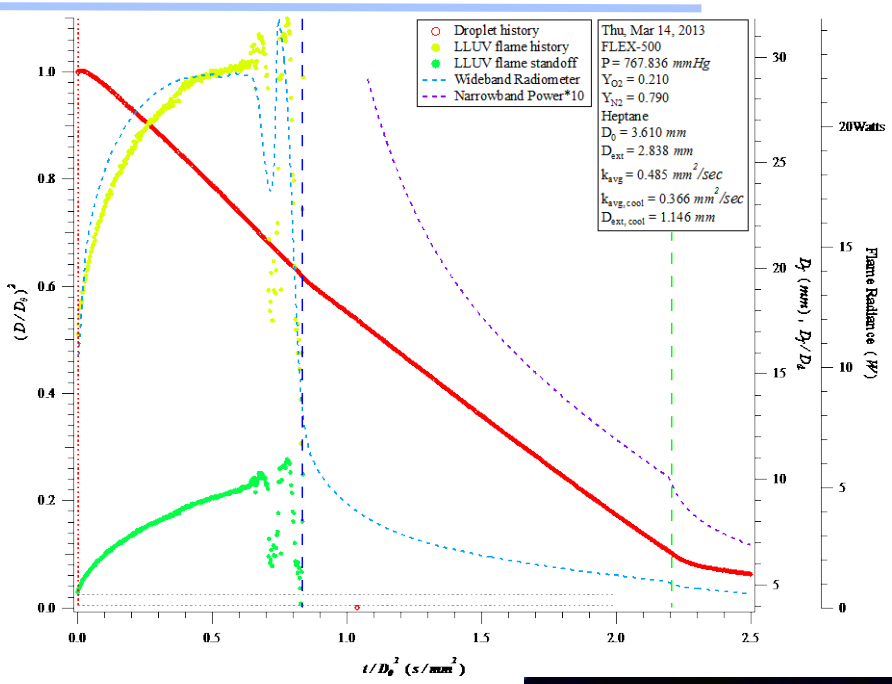


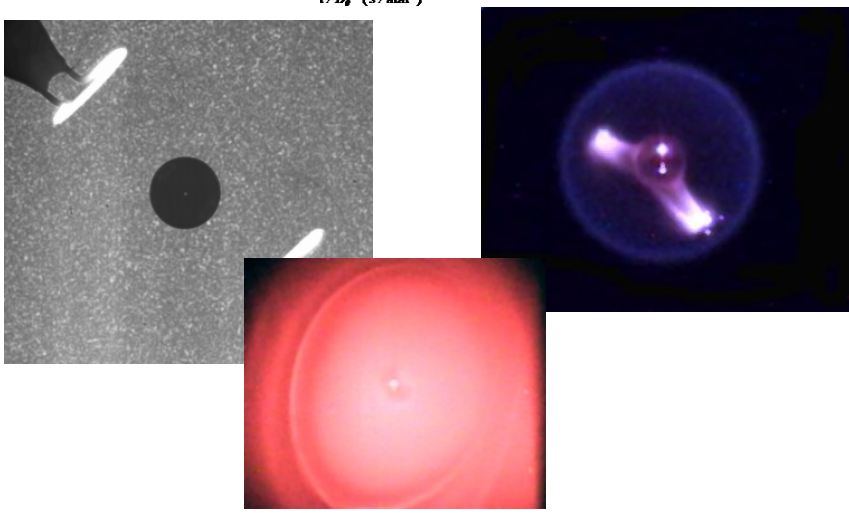
Cool Flame Results with modified camera



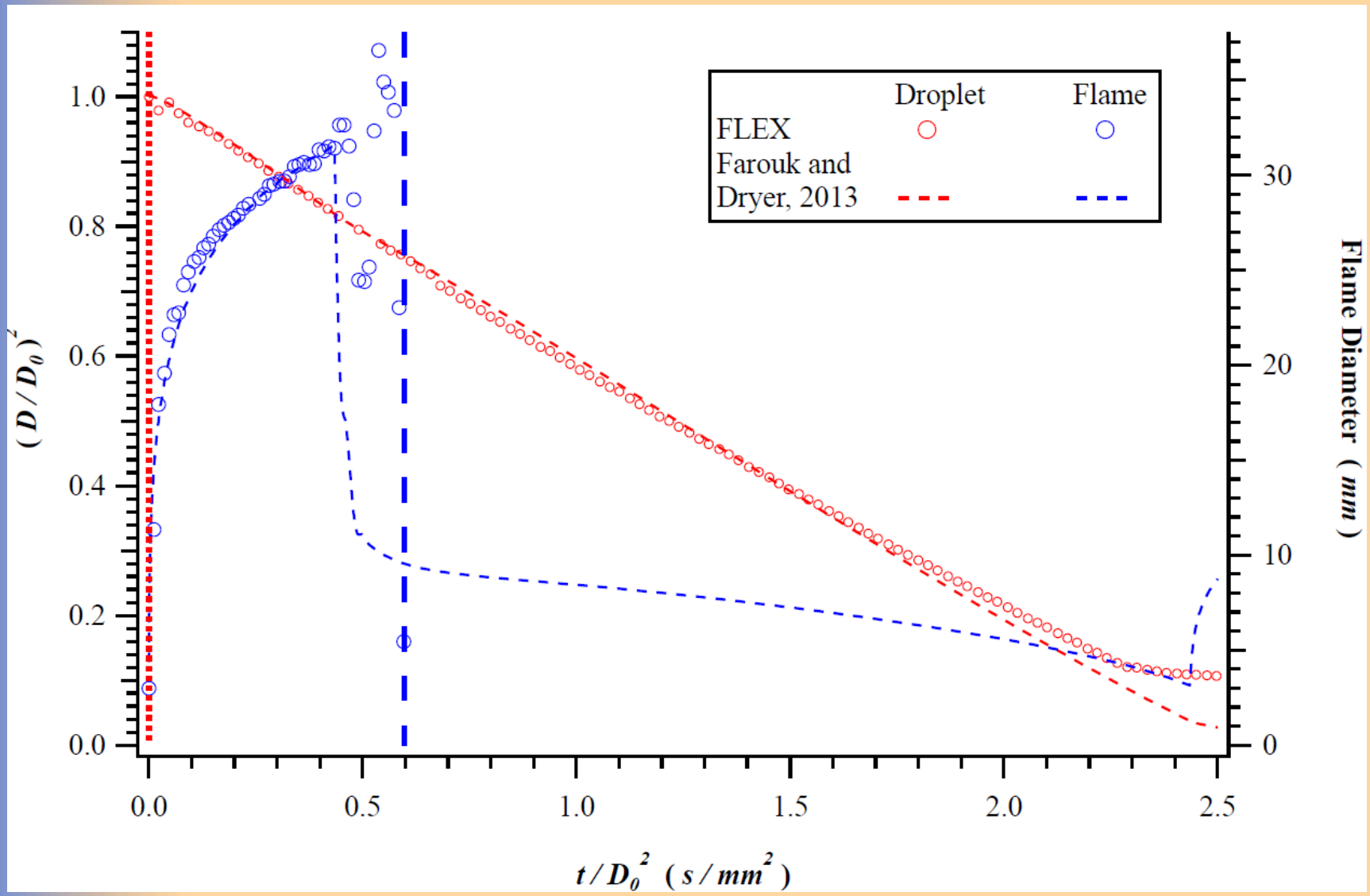
Cool Flames - Implications

- Spherically symmetric droplet combustion offers unique opportunity to study cool flames
  - Have achieved cool flame burns of over 120 *s*
- Predicted cool flame extinction droplet diameter, very sensitive to kinetic model
  - Some models don't predict cool flames at all
  - Farouk and Dryer identified key reactions to improve low temperature chemical kinetic models



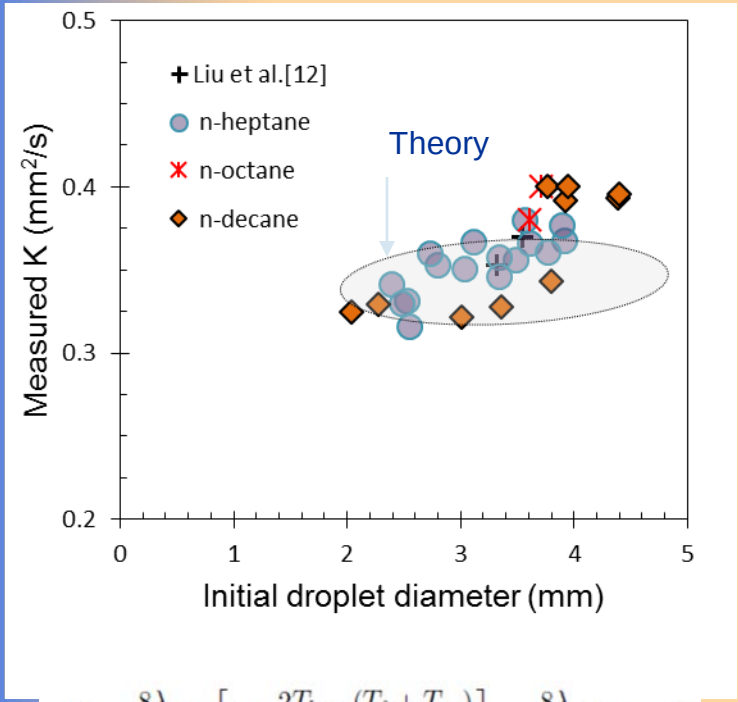


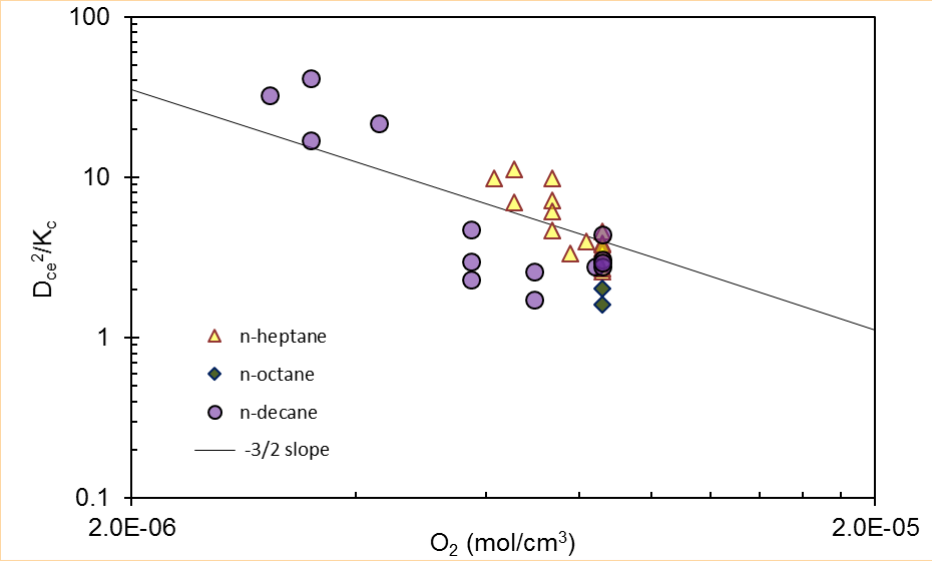
Comparison with detailed chemistry model



Theoretical Models using Liñán's Partial Burning Regime

- Cool flame burning is modeled using Liñán's partial burning regime
- Burning rates are predicted reasonably well
- Flame standoff ratio is predicted accurately for a range of oxygen concentrations
- Extinction diameters are correlated using simplified chemistry





Theory predicts -3/2 slope shown in the plot

$$K = \frac{8\lambda}{c_p\rho_\ell}\ln\left[1+\frac{2T_b-(T_\ell+T_\infty)}{L/c_P}\right] = \frac{8\lambda}{c_p\rho_\ell}\ln(1+B)$$

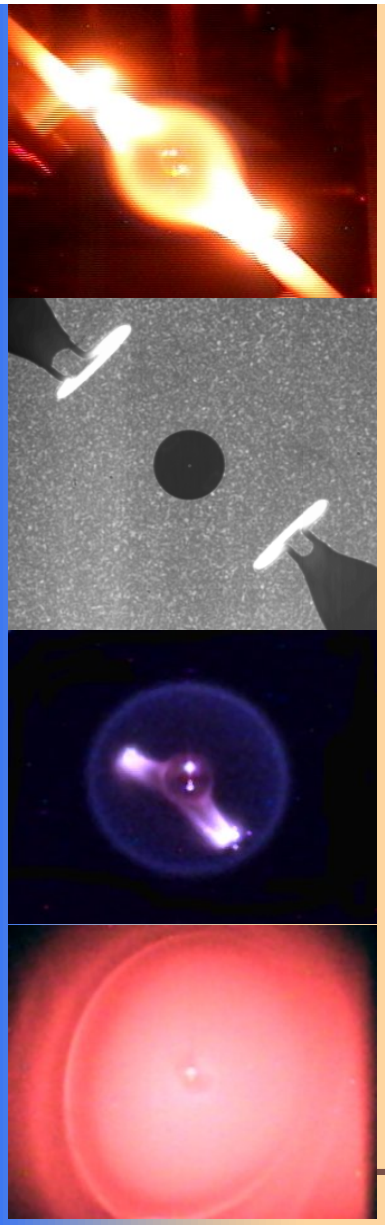
$$\frac{r_b}{r_\ell} = \ln(1+B)/\ln\left[\frac{1+B}{1+c_p(T_b-T_\ell)/L}\right]$$

→ Flame standoff ratio ~3.1 agrees with experiments and numerical simulations

Unresolved Issues

- While the reduced chemical kinetic models predict ignition delay times well, they are unable to correlate the cool flame burning rate and extinction data for varying pressures
- Alkane-alcohol mixtures show puzzling trends where both cool and hot flames seem to exist – observed trends are contrary to normal intuition
- Re-ignition to hot flames were observed only for fiber-supported droplets at higher pressures – fiber has profound influence on re-ignition
- Cool Flame Investigation seeks to resolve some of these issues

Cool Flames Investigation (CFI)



- SDT Members – F.A. Williams (UCSD), F.L. Dryer (Princeton), T.I. Farouk (USC), V. Nayagam (CWRU), D.L. Dietrich (NASA GRC)
- Study pure alkane, bio-fuel and mixtures of alkane and iso-alkane
  - Pure dodecane
  - Pure Farnesane (2,6,10 trimethyldodecane)
  - Dodecane/iso-dodecane mixtures
- Ambient pressures ranging from 0.50 to 5.0 *atm*
- Vary ambient O2 with N2 and Xe dilution
- Actively looking for outside collaborations to utilize the results of CFI

Future Investigations: Advanced Combustion via Microgravity Experiments

Objective

Improve fundamental understanding of:

- combustion structure and stability
- soot inception, surface growth, & oxidation
- emission reduction through N2 exchange
- flame chemi-ionization behavior & ion-driven wind
- materials flammability in microgravity

Relevance

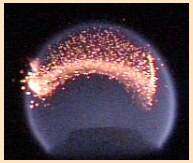
- Improved computational combustion models including sub-models for soot processes.
- Soot and NOx reduction in practical combustion.
- Spacecraft fire safety.

Impact/Applications - Earth-based

- Improved efficiency & reduced pollution.
- High-efficiency, low-emission combustors which operate at near-limit conditions.
- Improved design tools for combustion systems leading to reduced costs & design time.
- Novel control capability enabling improved combustor performance.
- Improved materials selection for spacecraft.

Facilities

ACME modular mini-facility for the Combustion Integrated Rack (CIR) enabling 5+ experiments:



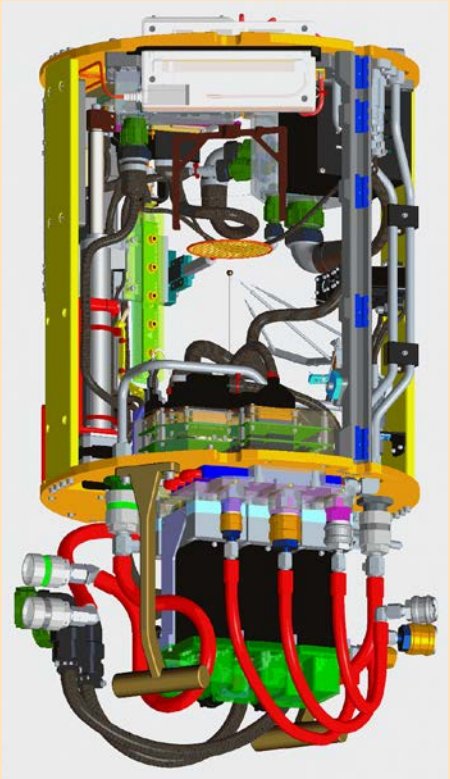
Burning Rate Emulator (BRE)

Coflow Laminar Diffusion Flame (CLD Flame)

Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)

Flame Design (*soot inception and transport)*

Structure and Response of Spherical Diffusion Flames (s-Flame)



ACME chamber insert with exchangeable burner, flow controllers, flame diagnostics

Future Investigations: Solid Fuel Ignition and Extinction (SoFIE)

Objectives:

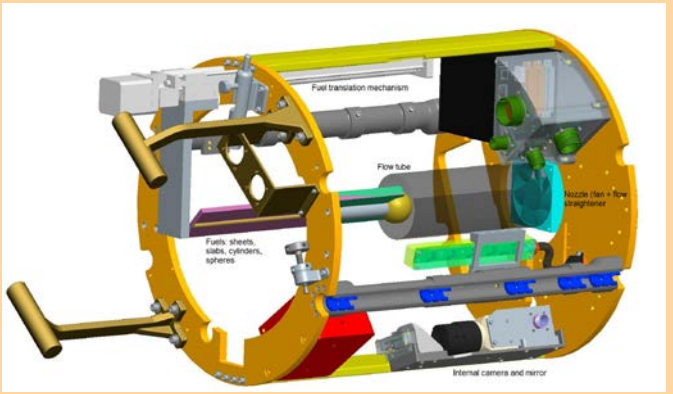
- To study ignition and flammability of solid spacecraft materials in practical geometries and realistic atmospheric conditions
- Evaluate the effects of oxygen, pressure, flow velocity and direction, external radiant heat flux, sample geometry, and fuel thickness on ignition, flame growth, and flammability

Relevance/Impact:

- Determine improved flammability test methods for cabin materials
- Update NASA materials flammability test protocols to address enhanced flammability of low-gravity fires
- Improve understanding of ignition limits and early fire growth behavior
- Validate material flammability numerical models

Facilities

- New CIR insert



Impact/Applications – Earth-based

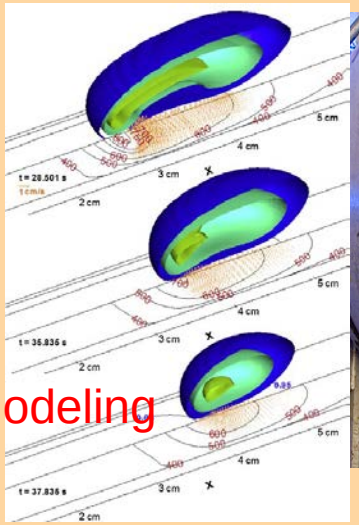
- Improved understanding of ignition, flame growth, and flammability of materials.

Solid Fuel / Fire / Flammability *Applications*

It is impossible to eliminate all risk of fire in spacecraft as long as there is fuel, oxygen, and a potential source of heat.

We reduce the fire risk by improving our understanding of

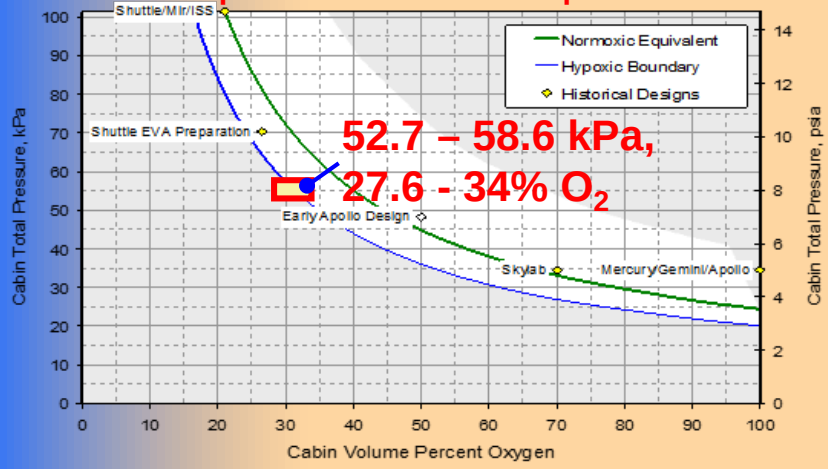
- *Material flammability*
- *Ignition sources*
- *Atmosphere effects (O_2, P, flow)*
- *Fire modeling*



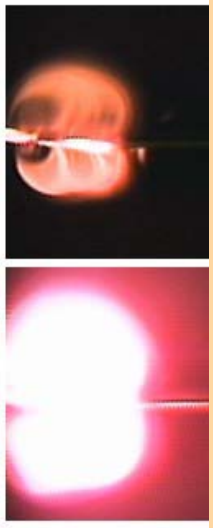
Fire Modeling

Materials Flammability Screening

Spacecraft Atmospheres



Ignition



Flow Effects

Human hair, 30% O_2

Flammability Limits At Reduced-g Experiment (FLARE)

Objective:

To develop a methodology to correlate material flammability limits in normal gravity and microgravity, which allows quantitative estimation of material flammability limit in microgravity based on the reproducible flammability data obtained on the ground.

Relevance/Impact:

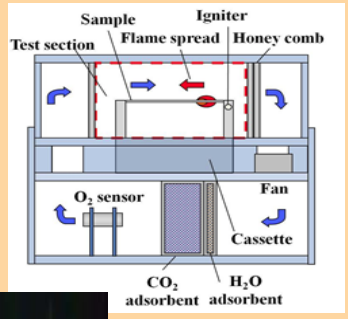
Fundamental Science – studying materials flammability in space allows us to accurately control the flow field and thus elucidate the importance of a critical Damkohler number (flow time /reaction time) on flame extinction.

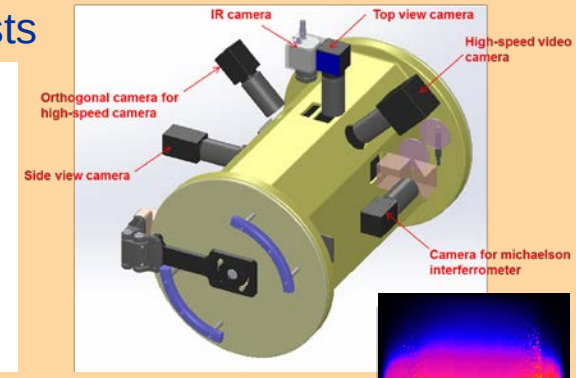
Facilities

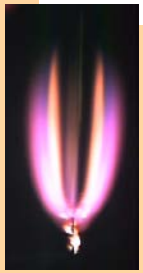
- JAXA to use existing KIBO/ MCIR/MSPR

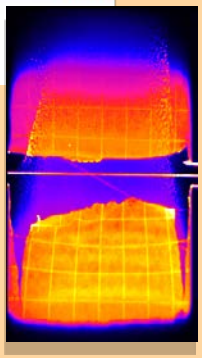
Impact/Applications – Earth-based

- Improved normal gravity materials screening tests









International Standard for Fire Safety in Space

Recommendation for the fire safety standard

Science team

- Sub-team 1: Science for the flat sample (Test1)
- Sub-team 2: Science for the wire combustion (Test4)
- Sub-team 3: Science for the ignition and arc-tracking (Test2,18)
- Sub-team 6: μG test facility and instrumentation

Flamma-bility limit prediction theory

Sub-team 5
- Tests of practical material on the ground
- Evaluation of new test methods
- Discussion among the members

Validity of the test methods

New test method team

- Sub-team 4: · LOI method · Reduced pressure method
- Sub-team 6: μG test facility and instrumentation

High Pressure Combustion Research (HPCR)
Supercritical Water Mixture Experiments (SCWM-series)

Supercritical Water Mixture (SCWM) – 2010 through 2021

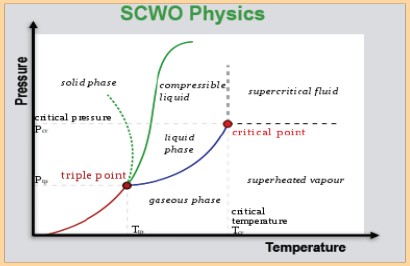
SCWM Series … an international set of investigations using the **DECLIC Facility**, built and operated by CNES, designed as *precursor* investigations to a follow-on Supercritical Water Oxidation research program

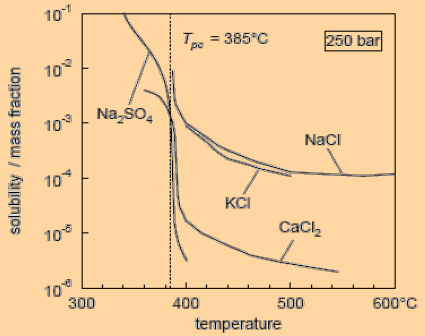
Objectives:

- **SCWM** … observe and quantify shift in critical point, determine onset of salt precipitation and salt transport in the presence of a salinity and temperature gradients (ISS operations end FY'16)
- **SCWM-2** … using a binary or tertiary system relevant to SCWO processes (e.g., CO2/Na2SO4/H2O) obtain high resolution measurements of phase transition points and transport properties (ISS operations end FY'19)

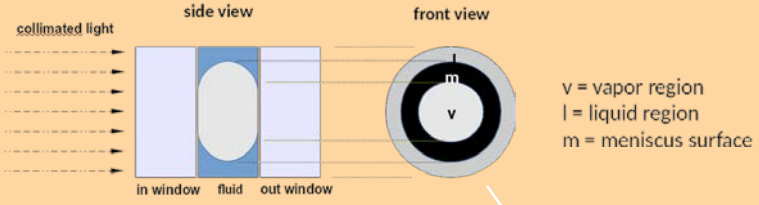
Relevance … investigation develops understanding of fundamental processes that occur during phase transitions at near-critical conditions

- develop mitigation strategies for fouling/corrosion due to salt deposits on critical surfaces ... the major obstacle preventing widespread use of this technology
- provide information for advanced reactor designs relying on internal heat sources for sustained operations



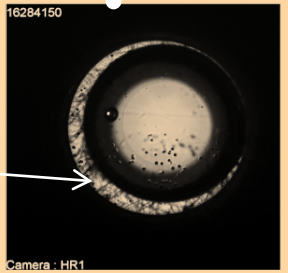


P-T curve showing supercritical region (left) salt solubility curves showing dramatic change in solubility in supercritical water (right)



(top)

(left)



(right)

Schematic illustrating vapor liquid regions (top), test cell (left) and regions in liquid where "vapor channels" (right) begin to appear (~373C) due to local boiling at walls

What's next?—Proposed Content

High Pressure (Super and subcritical) Droplet Combustion

Objective

Obtain benchmark data on the vaporization and combustion of droplets in sub- to super-critical conditions. Improve the fundamental understanding of the sub- to super-critical transition for single droplets and develop sub-models for complex CFD design codes.

Relevance

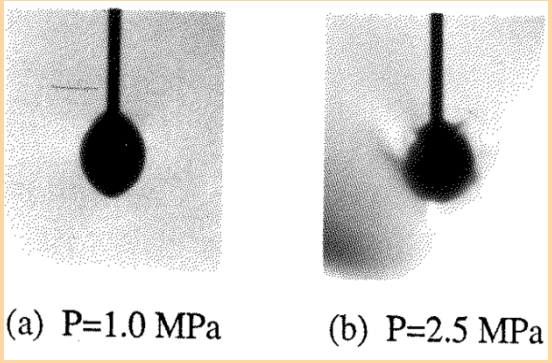
Virtually all practical combustors operate at high pressures due to higher thermodynamic efficiencies. High pressure combustion in the sub- to super-critical transition region poorly understood. Difficult to study under normal gravity due to increased buoyancy effects and reduced surface tension. Fundamental data needed to improve modeling of real combustors.

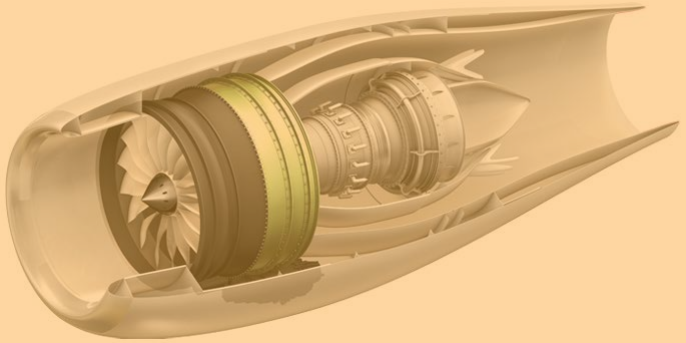
Facilities

Requires high-pressure insert to CIR or a new facility. Ground-based program necessary for engineering/science development.

Development Approach

- Establish Science Definition Team in collaboration with other Agencies.
- Define experiment beginning in 2018 and conduct experiment in 2022





Supercritical Water Oxidation (SCWO)

Hydrothermal Flames … advanced SCWO reactors will rely on internal heating provided by hydrothermal flames similar to conventional combustion burners

Objectives:

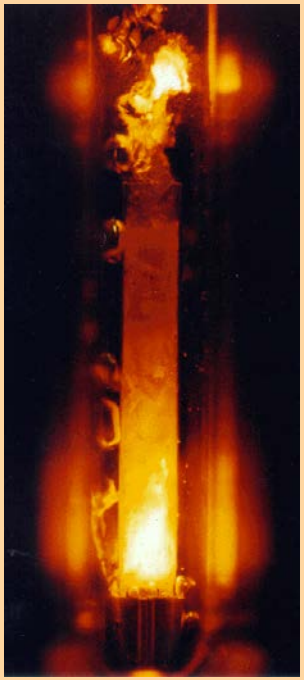
- Determine ignition parameters, flame structure, temperature profiles and reaction mechanisms of hydrothermal flames
- Study supercritical fluid dynamics of injected reactant streams; e.g., flow structure, turbulent transition, reactant mixing, critical transition phenomena

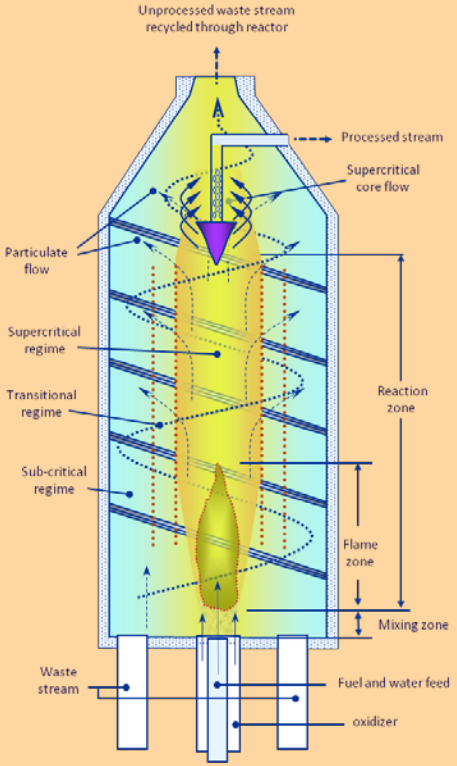
Relevance:

- Significant reductions in mass and volume, making SCWO feasible for space and extraterrestrial applications

Facilities:

- Research will require a new High Pressure Combustion Research Facility (HPCRF)

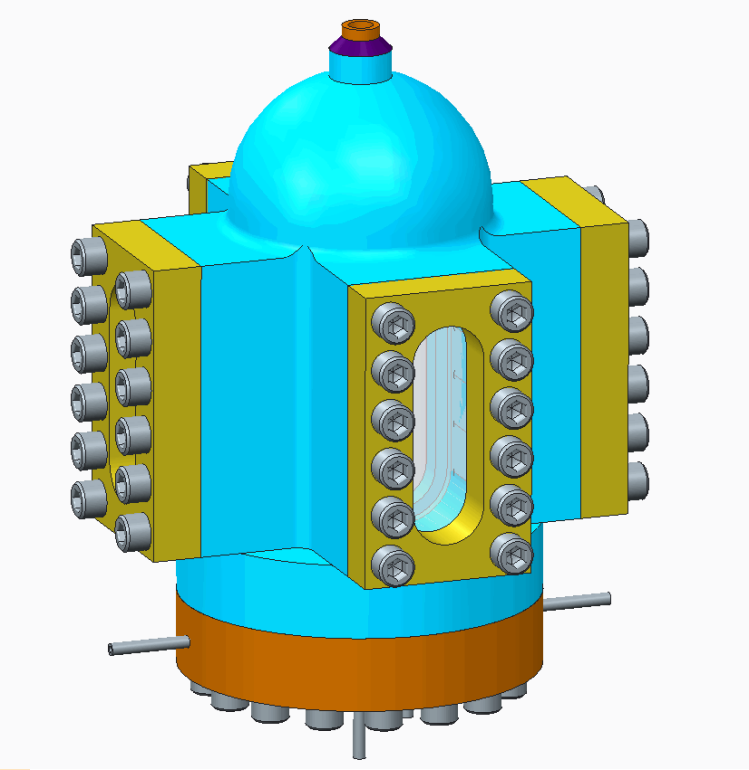




Hydrothermal flame (left) *in a supercritical water mixture of methanol at 250 bar using a co-flow burner (Wellig, B. , 2003) and conceptual SCWO reactor* ***(right)*** *using flow-stabilized hydrothermal flame for internal heating of reactant flow stream*

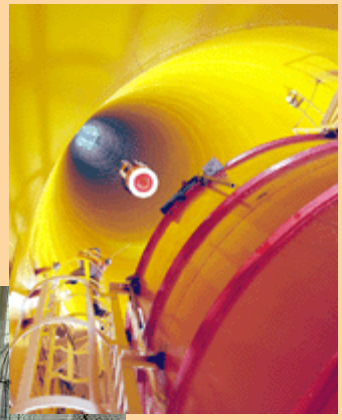
Future Facility Concept

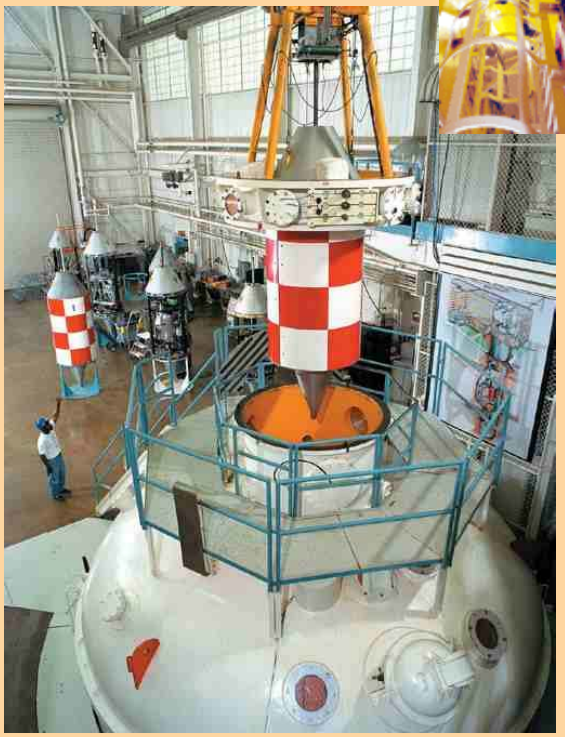
- Design Objectives:
  - Accommodate both constant pressure and constant volume operations
    - MAWP = 250 atm
    - maximum wall temp = 600 C
  - Diagnostics to inlcude:
    - imaging with two orthogonal views
    - Raman spectroscopy
    - temperatue, pressure, and radiometric sensors
  - On-orbit reconfigurable base will accommodate a wide range of experimental configurations (e.g., droplet, opposed flow, co-flow, etc.)



NASA Zero-g Facility

- GRC Zero-g Facility became operational in 1966
- No major mods since then
- Over 4900 drops
- Utilization rate: 2 drops/day
- Operational cost: $5.8 K/drop;
  74 labor hrs/drop
- Microgravity Duration: 5.18 s
- Free Fall Distance: 432 ft (132 m)
- Gravitational Acceleration: <0.000,01 g
- Deceleration: 35/65 g mean / peak
- Payload - Cylindrical, 42 in. (1 m) diameter
  by 13 ft. (4 m) tall
- Gross Vehicle Weight: 2500 lbs. (1130 kg)
- Experimental Payload Weight: up to
  1000 lbs. (455 kg)





Zero-g Facilities Background

- Current world-wide Drop Tower capability is little changed in decades despite major technology growth.
- Exceptions
  - ZARM-Bremen -- launch capability provides 10 seconds of micro-g
  - Portland State University -- rapid drop turnaround provides 2 seconds of micro-g with increased productivity and innovation
- Planetary exploration plans raise new research needs in partial gravity that cannot be satisfied on low-g aircraft alone (NASA terminated support in 2015).
- Partial gravity research largely ignored despite substantial technical importance for both fundamental science and exploration needs.

A design study has been initiated to convert to a mag-lev system that would cut operating costs by an order of magnitude and provide 10 s of user selectable g-levels.

Spacecraft Fire Safety Demonstration (Saffire)

<u>Experiment Objectives:</u>

Determine the fate of a large-scale microgravity fire

1. Spread rate, mass consumption, and heat release
   - *Is there a limiting size in microgravity?*
2. Confirm that low- and partial-g flammability limits are less than those in normal gravity
   - *Are drop tower results correct?*

Project developed and funded by NASA
Supported by international Topical Team (ESA)

Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.

FAA full scale aircraft test

Controlled burns of structures

Naval Research Laboratory Ex-USS Shadwell

Orbital Science's Cygnus approaching ISS

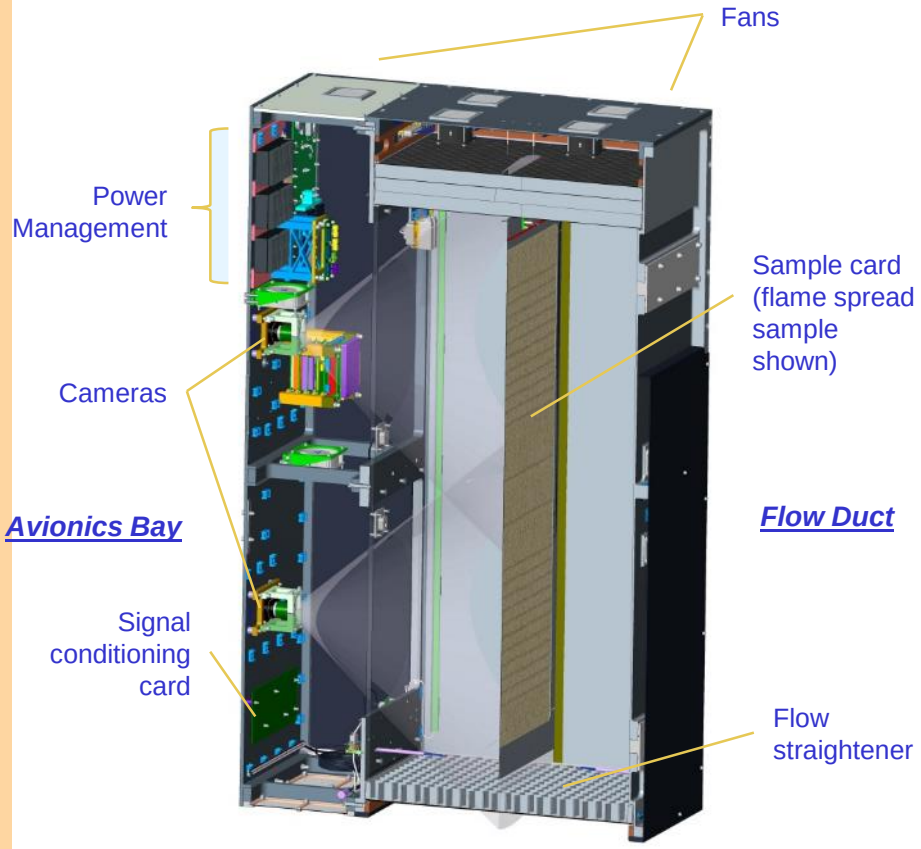
Saffire Overview

Needs:

- *Low-g flammability limits for spacecraft materials*
- *Definition of realistic fires for exploration vehicles*
  - *Fate of a large-scale spacecraft fire*

Objectives:

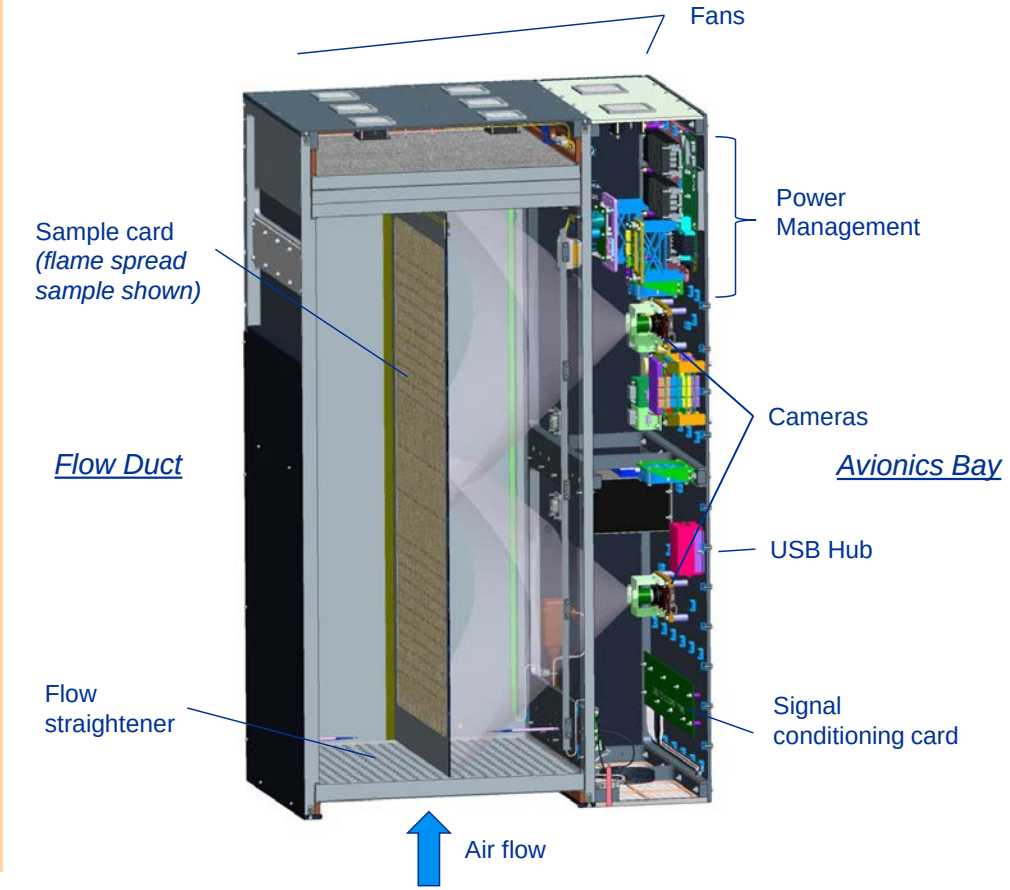
- *Saffire-I*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)
- *Saffire-II*: Verify oxygen flammability limits in low gravity
- *Saffire-III*: Same as Saffire-I at a different flow condition

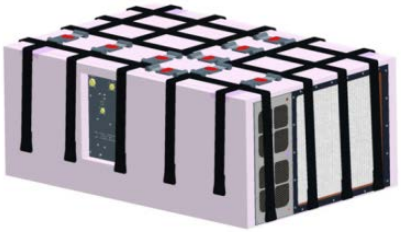


Saffire module consists of a flow duct containing the sample card and an avionics bay. All power, computer, and data acquisition modules are contained in the bay. Dimensions are approximately 53- by 90- by 133-cm

- *Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios*
- *Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.*

SAFFIRE Experiment Layout



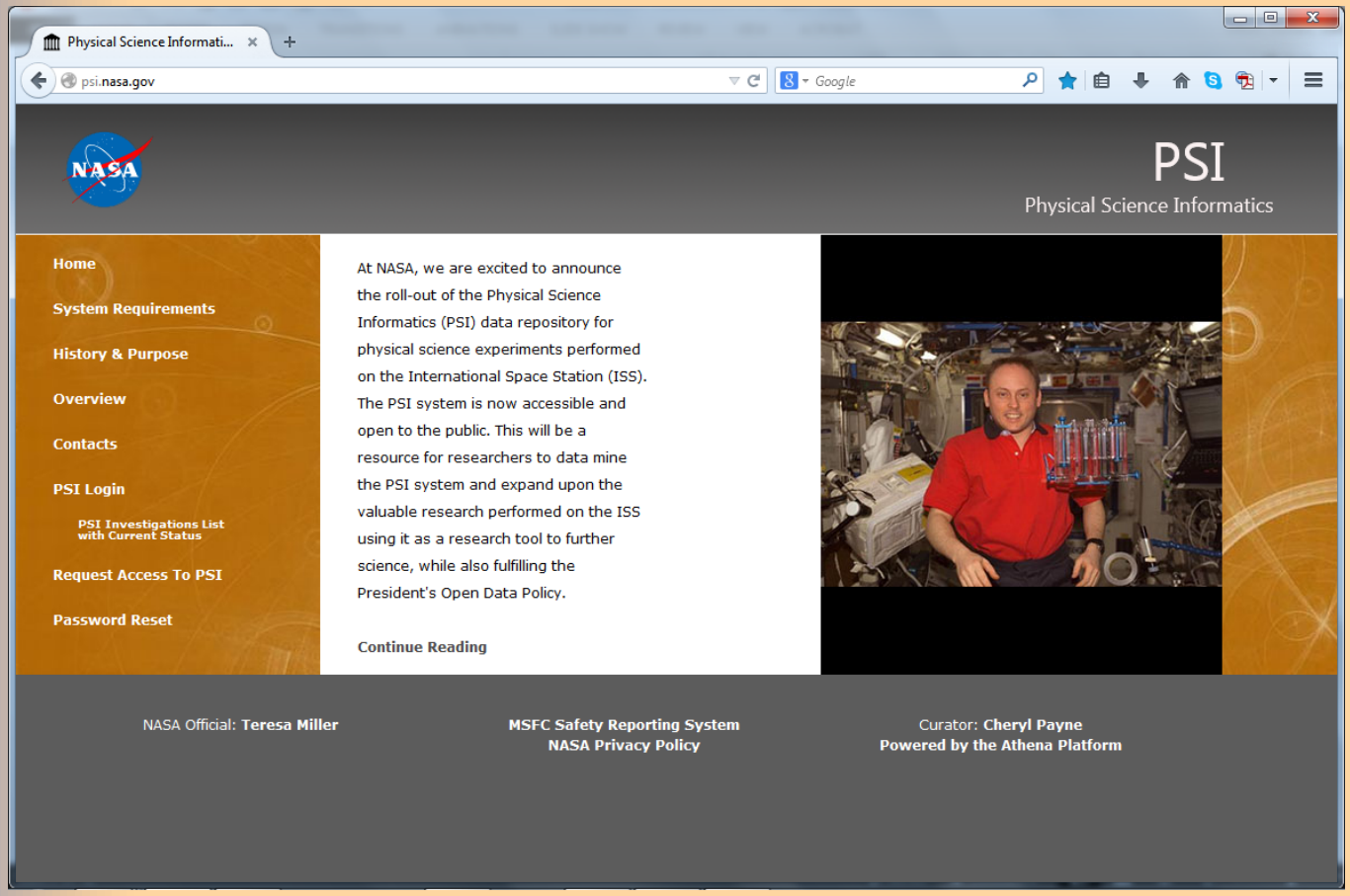


. Dimensions are approximately 53- by 90- by 133-cm

Physical Sciences Informatics

All NASA Life and Physical Sciences Data are being loaded on servers to be available to all

For Physical Sciences: psi.nasa.gov



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https://maptis.ndc.nasa.gov/Athena/ViewRecords.aspx?pk=4

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Overview:

NASA's Physical Sciences Research Program, along with its predecessors, has conducted significant fundamental and applied research, which has led to improved space systems and produced new products offering benefits on Earth. NASA's experiments in the various disciplines of physical science reveal how physical systems respond to the near absence of gravity. They also reveal how other forces that on Earth are small compared to gravity can dominate system behavior in space. The International Space Station (ISS) is an orbiting laboratory that provides an ideal facility to conduct long-duration experiments in the near absence of gravity and allows continuous and interactive research similar to Earth-based laboratories. This enables scientists to pursue innovations and discoveries not currently achievable by other means. NASA's Physical Sciences Research Program also benefits from collaborations with several of the ISS international partners—Europe, Russia, Japan, and Canada—and foreign governments with space programs, such as France, Germany and Italy. The scale of this research enterprise promises new possibilities in the physical sciences; some of these possibilities are already being realized both in the form of innovations for space exploration and in new ways to improve the quality of life on Earth.

Research Areas:

Biophysics: biological macromolecules, biomaterials, biological physics and fluids for biology

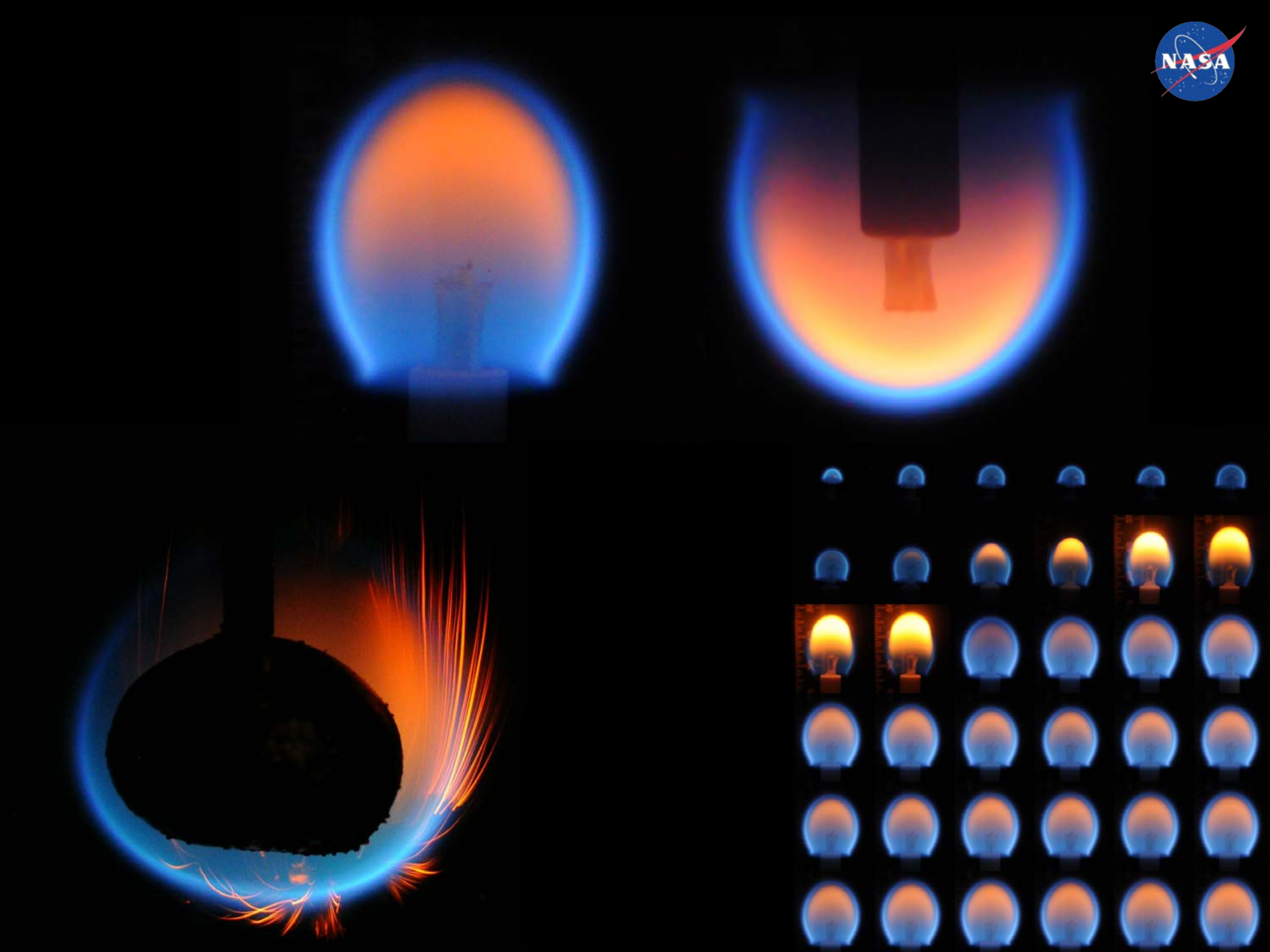
Combustion Science: spacecraft fire safety, droplets, gaseous - premixed and non-premixed, solid fuels and supercritical reacting fluids

Complex Fluids: colloids, liquid crystals, foams, gels and granular flows

Fluid Physics: adiabatic two-phase flow, boiling, condensation, capillary flow, interfacial phenomena and cryogenics

Opportunities

- Open Science – PSI database it open to all. Some funding from NASA.
- Future experiments and current facilities are potentially available to outside corporations and agencies through CASIS.
- High Pressure Super Critical combustion facility - a novel opportunity with significant challenges but real opportunity to provide needed data.
  - We are looking to collaborate with other agencies on the concept definition and utilization.
  - Suggestions on the best approach are welcome.


NASA